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# Artificial ligamentous joints : methods, materials and characteristics

Nick Hockings, Pejman Iravani and Chris R. Bowen

**Abstract**—This paper presents a novel method for making ligamentous articulations for robots. Ligamentous joints are widely found in animals, but they have been of limited application in robotics due to lack of analogous synthetic materials. The method presented combines 3D printing, tow laying and thermoplastic welding which enables manufacturing of this type of structure.

## I. INTRODUCTION

Locomotion and manipulation require interaction with an uncertain physical world. Consequently robotic limbs and hands need robust joints, with good range of motion. Vertebrate anatomy provides evidence of one physical solution - ligamentous synovial joints - that remains superior to other methods. This is highlighted by the work of Melchiorri et al (2013) who stated,

*“The replication of the human hand’s functionality and appearance is one of the main reasons for the development of robot hands. Despite 40 years of research in the field, the reproduction of human capabilities, in terms of dexterous manipulation, still seems unachievable by the state-of-the-art technologies.”* [16]

and of Grebenstein (2014),

*“The gap between the basic principles and solutions of bio-mechanical systems and the capabilities of technical systems is too wide to develop a proper hand design by simply copying the human hand using methods and solutions of the current robotics state of the art. It is currently still not possible to construct an exact copy of the human hand.”* [12]

The challenge is how to reproduce the material properties of the soft tissues involved, and how to layup those materials to reproduce the mechanism of anatomical joints. This is commonly considered a difficult task, e.g.

*“many joints are held together ... by ligaments or tough soft tissues which are almost impossible to duplicate”* [4]

This paper presents a method for making ligamentous articulations for robots, using 3D printing, tow laying and thermoplastic welding.

The approach applied here is to examine the established anatomical and histological knowledge of the structures being emulated and ask - *what properties of these materials and structures are sufficient to predict the useful behaviour that we wish to reproduce?*

Specifically, histology reveals that anatomical tissues are fibrous composites. Most of these tissues are hyperelastic and anisotropic, as such they cannot be approximated in a simple way by rigid body models. The behaviour of such

materials is determined by the arrangement and properties of their constituent materials : the diameter and stiffness of the fibres, the elasticity and hysteresis of the matrix, and the adhesion between the fibres and matrix. The kinematics are largely dependent on the topology and length of the fibres. The structure of anatomical tissues is known through all scales down to molecular structure. The choice of scale at which to emulate the materials determines the design.

### A. Review of quasi-ligamentous joints in robots, machines and orthopaedics

In robotics flexural joints have been used in 3D printed structures, notably the iRobot-Harvard-Yale hand [18]. These allow buckling and axial twisting of the joint, and can be built into a shape deposition cast skeleton. The flexible mechanism is robust to collisions, but this flexibility limits the ability to stably transmit force along the column of bones.

Another example of fibrous joints are the ribbon joints of the “Kilck-Klack” or “Jacobs Ladder” falling blocks illusion toy, [1] [19]. The mechanism is close to that of a four bar linkage, and to the cruciate ligaments of knees. The fibrous constraint is very stable, but the contact area between the blocks is minimal for all but one point in the range of motion. Consequently the motion is well constrained, but any compressive force would produce high pressure loadings at the contact surfaces.

Etoundi et al [8] [7] produced a condylar knee mechanism that used nylon cord ligaments in a four bar linkage, emulating the cruciate ligament mechanism of knees. Cords were also used as ligaments in ECCE Robot [15] to prevent dislocation of the shoulder joint. These were composed of stiff cords of ultra high molecular weight polyethylene (UHMWPE), or series combination of elastic and stiff cords. While these cord-ligaments reproduce some of the topology of anatomical ligaments, they lack the broad attachment and integration with the bones that make anatomical joints robust.

Van den Broek et al [22] [21] developed a prototype artificial inter-vertebral disk (AID) emulating the structure of anatomical inter-vertebral disks. The AID was composed of an ionized hydrogel core, wrapped in a hydrophobic membrane, enveloped by five layers of UHMWPE fibre, reproducing the nucleus pulposus constrained by the annulus fibrosus. Loading and fatigue testing showed that the prototype could withstand the maximum biological loading and fatigue, while providing stiffness and hysteresis close to that of healthy anatomical inter-vertebral disks.

The closest approximation of a ligamentous joint in a robot may be the silicone rubber joint capsule tested on the Anatomically Correct Testbed (ACT) hand [27]. This

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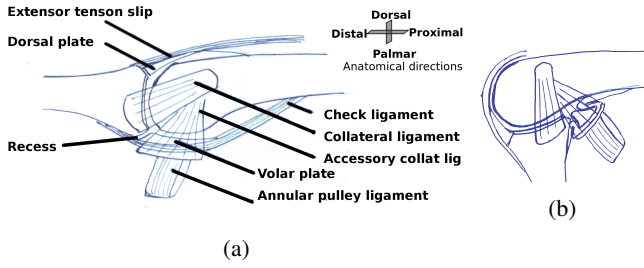


Fig. 1: (a) Proximal interphalangeal joint extended (b) flexed, showing the movement of the ligaments, dorsal and volar plates. The flexor tendons pass through the annular pulley.

lacks the stiff fibrous constraint of articular ligaments, but does preserve the large radius, compression bearing articular faces.

## II. TECHNIQUE

### A. Anatomical structures

This section describes the scale level at which the anatomical structures were emulated, and provides the keywords for roboticists to access the relevant anatomical literature.

The anatomy of human hands and dogs paws were used as the template for the demonstration specimens. Despite their differences of proportion, these are composed of the same tissues and share the same basic topology of bones and ligaments.

The variation in anatomy of healthy individuals shows that the material properties may vary by an order of magnitude without altering the function. Developmental anatomy shows that ligamentous joints are formed by progressive differentiation of tissues, and are fully functional whilst entirely soft prior to calcification of the bones. What is critical is sufficient strain tolerance and the ratio of stiffness between the different materials.

Ligaments do not generally provide the stiffness of constraint provided by engineering joints in rigid materials. For example for any given ligament it is generally possible to manipulate the joint to a position where the ligament is slack enough to pass a probe under it.

The stability of ligamentous joints is also dependent on direction of the load and the action of the tendons/muscles around the joint. By itself the joint capsule, including ligaments, prevents dislocation of the compression bearing articular surfaces, but commonly does allow some separation of the joint surfaces if tension is not opposed by muscle contraction. Ligaments are generally much less substantial than the principal tendons of the joint and usually have less leverage. Further, the series arrangement and under-actuation of joints is such that a load not supported by a tendon will commonly cause rotation of other joints that either transfers the load onto a tendon, or releases the load altogether. The exception to this being the function of suspensory and check ligaments which act on tendons in parallel with muscles in “passive stay” mechanisms.

1) *Tissues of synovial joints:* Articular cartilage is a thin layer of tough hyaline hydrogel with collagen fibre reinforcement in the plane. Synovial fluid is a viscous shear thinning fluid that acts as a boundary lubricant between the articular surfaces, and between the joint capsule and articular convex surface [9].

The joint capsule is continuous with the articular cartilage of the concave side of the joint. The hyaline content of the matrix is progressively replaced by hyper-elastic elastin. The capsule is reinforced with dense orientated collagen fibres. The matrix allows the capsule to stretch orthogonal to the collagen, and lubricates relative movement of the fibres in shear motions. The articular ligaments are dense bundles of collagen fibres in the joint capsule.

2) *Structure of finger joints:* The joints of the finger - distal inter phalangeal (DIP) [11], proximal inter phalangeal (PIP) [3] and metacarpophalangeal (MCP) - are of very similar construction. In the MCP the extensor tendon slip is replaced by the extrinsic extensor tendon, which does not insert on the distal margin of the joint but joins the extensor hood instead.

Figure 1 shows the PIP. Note the fibrocartilaginous dorsal [20] and volar plates, and the buckling motion of the volar plate aided by the recess between its distal margin and the proximal phalanx [3]. The check ligament and the distal part of the accessory ligament limit the maximum extension of the joint.

The collateral ligaments are much thicker and stronger than the accessory collateral ligaments, and form the primary constraint on the motion of the joint. In the MCP the collateral ligaments are attached and the joint faces shaped, such that the collateral ligaments are slack if and only if the joint is extended, allowing medio-lateral swinging of the joint. [17]

3) *Structure of the palm:* The palm is a complex structure, that provides critical load bearing and balancing in both paws and hands. Reproducing these functions by rigid mechatronic parts has been particularly difficult.

Figure.2 shows the ligamentous tissues of the palm. There is no synovial articular surface at the distal inter-metacarpal joints. Other soft tissue structures separate the bones including the sagittal bands of the metacarpophalangeal joints and the tendons of the interosseous muscles. The metacarpals are held to each other by (i) the inter-palmar-plate ligaments [2] that link the volar plates of the metacarpophalangeal joints to each other, collectively called the transverse metacarpal ligament, (ii) the natatory ligament which connects the proximal margin of the second annular ligaments of the first phalanges, (iii) the transverse fibres of the palmar aponeurosis [5] which are connected to the deep transverse metacarpal ligament by the septae of Legueu and Juvara [5] [2].

The proximal inter-metacarpal joints have small articular facets, and three sets of ligaments - dorsal, palmar and interosseous - which allow minimal rotation of adjacent bones about each other [6]. The carpometacarpal joints have short ligaments that allow very little movement.

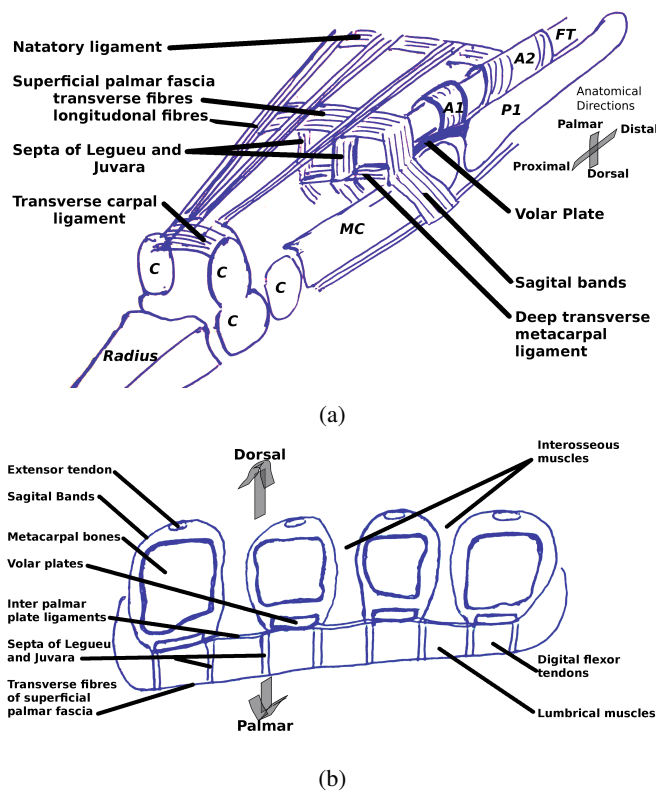


Fig. 2: (a) Palmar-oblique view of the ligamentous structures of the palm : A1-1st annular lig, A2-2nd annular lig, C-carpal bones, FT-digital flexor tendons, Mc-metacarpal bone, P1-first phalanx bone. (b) Transverse section of the palm at the level of the deep transverse metacarpal ligament (DTML). Note the DTML is composed of the volar (palmar) plates and the inter palmar plate ligaments.

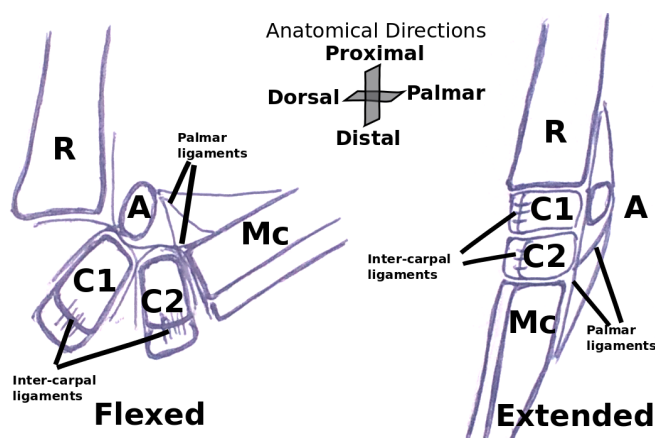


Fig. 3: Simplified diagram of ungulate-like carpal mechanism implemented - Flexed left, extended right. Ligaments stabilise relative dorsal-palmar movement between the bones, while allowing flexion about the palmar margin of the carpal bones. R-radius, C1 & C2-1st & 2nd row carpal bones, A-accessory carpal bone, Mc-metacarpal bones.

4) *Structure of carpus*: The carpal mechanism of ungulates (mammals with hoof feet) (fig. 3) was used rather than that of dogs because it has a simpler motion and was easier to construct. The carpal bones are arranged in two horizontal rows and flex by hinge motion about their palmar ligaments. As such it is close to a flexural joint when flexing, but bears compression on a continuous column of bones when extended. On the dorsal side the intercarpal ligaments connect only between bones on the same row. On the palmar side long ligaments from proximal row accessory carpal and radial carpal bones to the metacarpals limit the maximum extension of the intercarpal joint.

## B. Materials

1) *Compatible thermoplastics*: Three different thermoplastics, polycaprolactone (PCL), polylactic acid (PLA), polyamide (PA), were selected with different softening temperatures, table(I) and compatible inter-molecular bonding. PCL and PLA have the same intermolecular bonding based on ketone groups which form dipole attractions, consequently they are miscible when molten. Softened PCL wets very well to solid PLA forming a high surface area of contact with 3D printed PLA parts, (fig.4c). PCL-PLA adhesion approaches the strength of pure PCL or PLA.

Polyamides(PA) including polyaramide(PAr) have amide links between their monomers. These present both ketone groups and hydrogen bearing amide groups. The ketone groups of PCL or PLA can form N-H $\cdots$ O hydrogen bonds with the PA, which are stronger than the ketone dipole attractions within either PCL or PLA. This strong intermolecular bonding allows the PA ligaments to be firmly attached to the bones.

Glycerol (propane-1,2,3-triol) is a short chain polyalcohol which is miscible with PCL and can be used as a plasticising agent. PCL softened with glycerol was used to make some joint faces more compliant.

Styrene-ethylene-butadiene-styrene (SEBS) is a block copolymer that forms very soft (0 Shore-A [23]) hyperelastic oil-gels (SEBS-gel) with alkane oils. SEBS-gel is used as a hyperelastic matrix for soft tissues. SEBS-gel does not adhere to polar polymers but can be mechanically blended with PCL, or infused between PA fibres as a matrix. Varying the ratio of SEBS-gel:PCL produces blends of intermediate stiffness and elastic limit. A stack of rolled films of blends of SEBS and PCL of progressively varied ratios can be rolled together on a hotplate to produce a composite film with pure PCL on one face and pure SEBS-gel on the opposite face. These composite films were used both to adhere SEBS to PCL and to prevent adhesion between PCL surfaces in contact.

2) *Low temperature thermoplastic welding*: PCL undergoes transition from opaque rigid semicrystalline state to transparent amorphous glassy plastic state at around 60C. In this state it is viscoelastic with substantial surface tension. This allows PCL to be molded by hand and causes it to form a smooth surface if allowed to relax in the plastic state. Small spots in PCL material a few millimetres in diameter can be

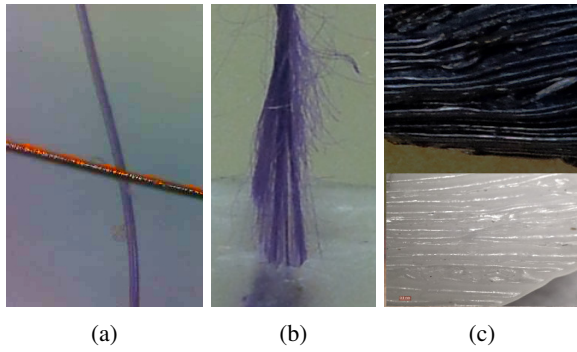


Fig. 4: (a) Thickness of polyamide (PA) fibre (purple) compared to 30micron motor wire. Fine fibres confer flexibility to ligaments and provide high surface area for adhesion to the matrix. (b) PA fibres failing under tension, before a 10mm long weld into a polycaprolactone (PCL) matrix, in a pull out test (c) PCL (white) forms close key with 3D printed polylactic acid (PLA, black), reproducing the 0.3mm ridge pattern of the surface. PCL-PLA adhesion approaches the strength of pure PCL or PLA

softening temperatures of plastics (deg C)		
Polycaprolactone (PCL)	60C [26]	glass transition
Polylactic acid (PLA)	150-160C [24]	melting point
Styrene-Ethylene-Butadiene-Styrene (SEBS)	170 210C [23]	melting point
Polyamide-6,6 (PA66)	135-254C [25]	melting point
Polyaramide (PAr)	>500C [28]	thermal decomposition

TABLE I: Softening temperatures of plastics, temperatures will vary with polymer chain length and compounding additives.

heated above the phase change with a soldering iron. This allows spot welding of PCL to itself and other compatible materials without softening adjacent structures, and for such welds to be resoftened and their position adjusted. Spot welding is used to precisely position ligament attachment points.

Tows of parallel non-spun polyamide (PA) fibres, either polyamide-6,6 (PA66) or polyaramide (PAr), approximately 25 microns in diameter, (fig.4a), were used for the tendons and ligaments. The combination of high surface area of the fine fibres, with good wetting of PCL to PA and strength of hydrogen bonding produced strong welds between PCL and PA. In pull-out tension testing PA fibres fail before their connection to PCL (fig.4b), hence the strength of PA ligaments is limited by the strength of the fibres not the attachment to PCL.

### C. Layup process

1) *Bone geometry from volume imaging:* The bones were 3D printed in PLA using a RepRap fused filament deposition printer [14]. The models of the bones were segmented from MRI and CT scans using Slicer3D software [10]. These bones as printed in PLA approximate geometry of the calcified tissues (cortical bone, cancellous bone, and calcified cartilage) which are distinct from noncalcified tissues in

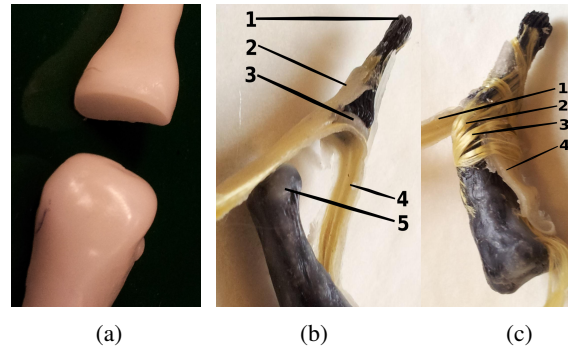


Fig. 5: Making articular surfaces (a) Method One forging polycaprolactone (PCL) articular surfaces against each other (b) Method Two laminated joint surfaces. Materials: 1. Poly-lactic acid (PLA) bone, 2. PCL-SEBS graded laminate, with PCL face bonded to PLA bone, 3. PCL-Glycerol blend, forms a compliant socket, 4. Polyaramide (PAr) fibres between PCL faces of laminate, form the palmar plate and dorsal extensor slip continuous with the socket, 5. PCL coating on polylactic acid (PLA) bones. PCL of articular surface faces SEBS of laminate hence faces cannot adhere, but do require oil lubrication, (c) DIP joint Method Two with ligaments: 1. Extensor slip, 2. Collateral ligament, 3. Accessory collateral ligament, 4. Volar plate

clinical imaging. This does not however include the articular cartilage which is a critical compression bearing tissue in synovial joints, but much more difficult to accurately segment from medical volume imaging.

The PLA printed bones were then overlaid with PCL. This provided a layer of low temperature thermoplastic firmly adhered to the PLA, that could be formed and welded without deforming the printed structure. In the region of the articular surfaces PCL softened with glycerol was used to better approximate the compliance of articular cartilage.

2) *Articular surfaces - method 1:* The articular surfaces were formed by forging opposing surfaces against each other with one bone chilled and the other heated above the phase transition of PCL. The cartilaginous part of the joint capsule was formed by drawing the warm PCL by hand from the concave side of the joint over the chilled convex side of the joint, (fig.5a). During the forging process the opposing faces were lubricated with a film of oil and kept continuously in relative motion to prevent fusing between them. The flexing of the joint during forging helps to ensure that the shape formed permits the range of motion required and that the articular surfaces are congruent throughout the motion.

3) *Articular surfaces - method 2:* A ribbon of composite SEBS-gel-PCL film, section(II-B.1), was laminated with polyaramid fibres on the PCL side. One ribbon was placed running palmar-dorsal on the concave articular surface of the distal bone, with the SEBS side facing the proximal bone. Additional ribbons were placed on the dorsal and palmar surfaces of the distal bone and laminated to the first ribbon to form the check ligament of the volar plate and extensor tendon slip, (fig.5b). Pads of blended PCL-SEBS-gel were



added to the portions of the volar plate and extensor slip adjacent to the distal bone, to emulate the fibrocartilaginous pads of the anatomical structures (fig.1a&5c).

4) *Articular ligaments and joint capsule:* Ligaments are attached by working warm PCL into a point near the end of a tow of PA66 with a soldering iron, then pressing this to the prewarmed insertion point in the PCL covering the PLA bone. This method allows good wetting of the PA66 by the PCL. The insertion point can then be adjusted by pulling on the tow either side of the attachment point. The PCL can then be cooled to solidify it and fix the attachment point.

The PA66 tow is then laid across the joint to locate the correct point for its ‘origin’ attachment. The fibres of the tow are worked into the attachment site and more PCL added as needed to ensure good adhesion of the fibres. The tension of the ligament can then be adjusted by pulling on the free end of the tow while flexing the joint while the attachment site is soft.

The joint capsule and the elastic matrix of the ligaments outside of the bone is applied by wrapping the joint in PCL-SEBS-gel film, then briefly melting the film with hot air from a heat gun.

### III. DEMONSTRATION

#### A. Finger

A set of fingers for a hand were printed and laid up using method 2, section(II-C.3), for the joints, following the pattern of the anatomy, section(II-A.2). Polyaramide(PAr) was used for the ligaments, in order to provide a wide temperature tolerance for infusing PCL-SEBS-gel matrix. Polyaramide deep and superficial flexor tendons and associated polyaramide flexor retinacular ligaments were fitted to the finger to assess the range of motion. Details of the tendon system are provided in [13].

The resulting fingers match the dimensions of the musculo-skeletal components of the hand in the MRI image, leaving the normal anatomical space for dermal and subdermal structures to be added. This is important because robot fingers are usually thicker than human fingers of the same length and lack the soft pads and other dermal structures. The joints (MCP, PIP and DIP) allow the normal anatomical range of flexion-extension, (fig.6a&6b).

Lateral stability of the DIP and PIP was slightly slacker (7 versus 5 degrees of yaw) than that of the human hand in the MRI image. Strength of lateral stabilization was tested by loading the PIP to 0.6Nm static torque without damage. This corresponds to a lateral load of 3kg weight supported by a single finger at two centimetres distal to the joint, which exceeds the maximum loads normally exerted in this way by adult humans in a domestic setting. Note that heavy loads would normally be lifted on the palmar surface of the finger with tension borne by the digital flexor tendons, which are many times stronger than the collateral ligaments.

The MCP reproduced the cam tensioning action of the collateral ligaments, allowing wide yaw (25 degrees) in the extended position, and much reduced yaw (10 degrees) in

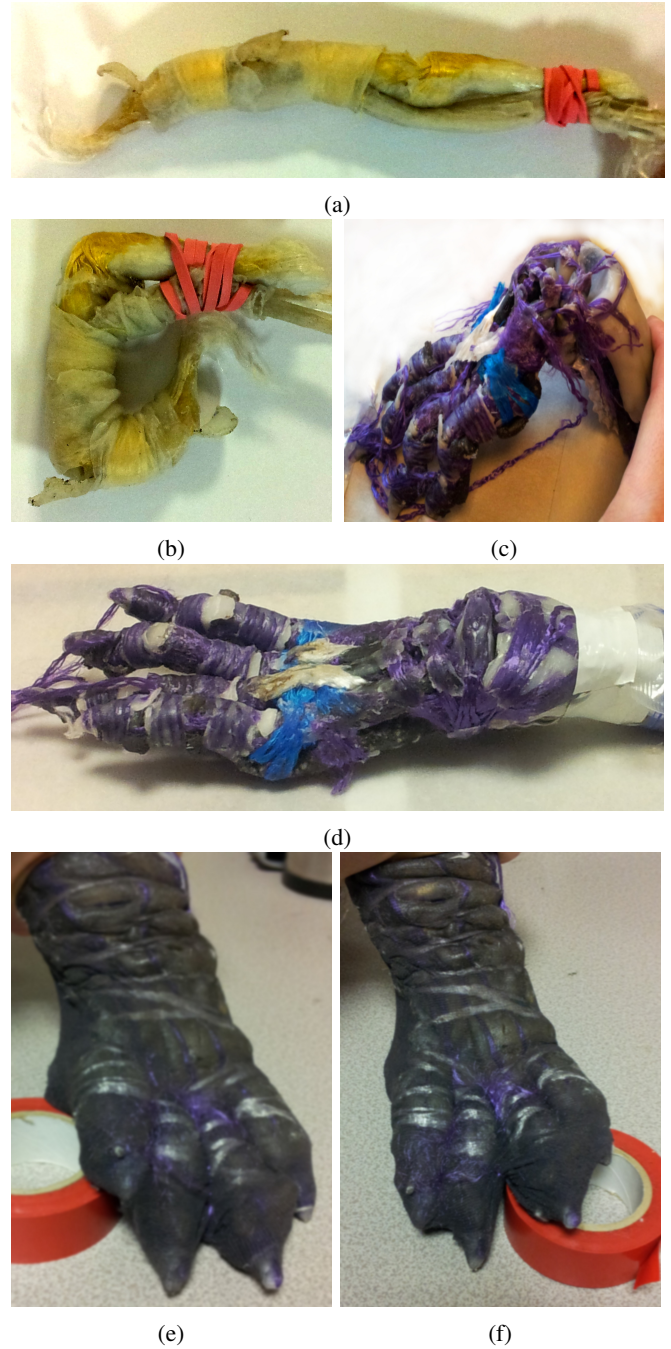


Fig. 6: Joint motions (a) finger extended, (b) finger flexed, (c) paw carpus flexed, (d) paw carpus extended, (e)&(f) passive supination/pronation of the paw.

the flexed position. This action helps to close the fingers in a cage around an object in the palm in humans.

In the extended position the MCP, PIP and DIP in series permitted a total axial roll of 45 degrees. This motion is important in allowing the finger tips to comply to the orientation of the contact surface.

Friction with the joints dry was high, as expected given the contact between soft SEBS-gel and hard PCL. When lubricated with paraffin (alkane) oil friction was very low

and comparable to synovial joints. This reflects that paraffin is the solvent component of the SEBS-gel, so wets very well to that surface, while the PCL surface is very smooth having been shaped by surface tension in the glassy phase.

The joint capsule was less satisfactory. The PCL-SEBS-gel film was not well fused into the ligaments. This was partly due to the heat gun being oversized and lacking fine temperature control, which made it difficult to deliver the right amount of heat without risking damage by excess heating.

#### *B. Paw*

The paw was printed and laid up using method 1, section II-C.2, for the joints, following the pattern of the anatomy described in section II-A. Polyamide-6,6 (PA66) was used for all ligaments and tendons.

The flexion of the carpus is approximately 120 degrees shown in (fig.6c,6d) matching that of dogs. The passive supination/pronation of the paw by differential extension of the carpo-metacarpal and inter-metacarpal joints is shown in (fig.6c,6d). This motion is important to comply with the shape of the terrain and distribute load across the paw.

The paw was based a CT scan of the front paw of a dog weighing 200N, and tolerates repeated static loads greater than 120N without flexor tendon actuation. In use the flexor tendons would bear part of the tension resisting hyperextension of the joints.

An important shortcoming of the paw is that method-1 for making the joints resulted in some of the MCP and PIP joints being unintentionally fused during the layup.

### IV. DISCUSSION

The key features of the materials produced are (i) the use of multiple matrix materials of stiffness ranging from rigid to low modulus hyper-elastic (ii) stiff reinforcing fibres in soft matrices creating extreme anisotropies (iii) that fibres cross matrix boundaries creating topological connections in a deformable structure, and (iv) specific fibre paths matched to the geometric shape of the rigid matrix regions. Together these features integrate material composition with mechanical structure to produce a functional machine as a single piece deformable mechanism.

The central component of the technique is the use of thermoplastic welding of the matrix of the composite to achieve accurate fibre placement. This allows tows to be individually laid, immediately fixed and adjusted during the layup. It also points to how the process could be automated to achieve precise and repeatable construction by laying tows and thermoplastic tapes.

The strength of the weld between a fine fibre and a compatible thermoplastic matrix makes it possible to have compact attachment regions for ligaments that match the anatomy being emulated. It also makes it straightforward to estimate the quantity of ligament fibre needed to impart a given strength to a joint.

To reproduce the function of anatomical fingers and paws at 1:1 scale it was necessary to emulate the tissue structure

at a scale between 300-100 microns. Human finger anatomy involves many layers of ligamentous and tendinous tissues, hence it is important that these are kept thin to achieve slender dextrous fingers.

#### *A. Comparison to other joint types*

Relative to pin-hinge joints, ligamentous joints provide a simpler path for compressive and tensile forces carried by the column of bones and the tendons respectively. In joints composed purely of rigid materials, such as pin-hinge joints there has to be a discontinuity in the tension bearing structure, and a conversion the tension to a compressive force that can be transmitted by contact between rigid parts. This requires that the force doubles back on itself around the pin or other retaining part, which requires more material and more space than a ligamentous joint made of materials of similar strength.

Compared to flexural joints, ligamentous joints have a greater capacity to bear compressive loads due to the large area of direct contact between the bones. This translates to the ability to support greater actuation force by tendons, for a given size of joint. Flexural and ligamentous joints share the ability to deflect to off axis loads, which is beneficial both for complying to unknown surfaces in grasping, and to avoid breaking in collisions.

#### *B. Actuation*

In animals both actuation and additional stabilisation is provided by tendons. Tendons in animals are held in their correct paths by a second set of ligaments known as 'retinacular ligaments'. Animal tendons are proportionally much thicker than those commonly used in robots. The load bearing fibres of tendons are parallel, held together by an elastic matrix. Bowden tubes and rotating pulleys are not found in animals. Friction of tendons is lubricated by fluid filled sheaths and hyalinized load bearing surfaces resembling synovial joints. Where lateral pressure is low, tendons are lubricated by solid hyperelastic tissue.

The methods and materials described in this paper lend themselves to emulating anatomical tendon networks. The techniques for this will be addressed in another paper.

#### *C. Further work*

Further work will involve creep and fatigue cycle testing to assess durability and reparability of structures built in this way. Materials development may include new thermoplastic blends, custom co-block polymers, and custom 3D printer G-code for emulation of gross bone structure. Thermoplastic tape and tow laying tools could improve build consistency. Given suitable CAD-CAM modelling and process monitoring it would be possible to automate the lay up process.

Further components that are needed are dermal structures (pads, dermis, nails, claws and hooves), actuators, and embedded sensors for tactile and proprioceptive sensation.

## V. CONCLUSIONS

Contrary to previous expectations [12] [4] direct emulation of the mechanical properties of histological tissues and anatomical structures is feasible. The key distinction is to emulate the mechanical, but not necessarily the chemical or biological properties of the materials.

The ability to produce tough ligamentous joints opens the possibility of exploiting known anatomical mechanisms whose function is hard to match with conventional mechatronic techniques.

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